

Advanced Nanomaterials: Engineering, Surface Functionalization, and Applications in Environmental and Biomedical Fields

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Abstract

This habilitation thesis summarizes over two decades of scientific and academic activity (2001–2025), highlighting original contributions in chemical engineering, materials science, nanotechnology, functional textiles, and biomedical applications. The work reflects the coherent development of an interdisciplinary research profile centered on the design, synthesis, characterization, and surface functionalization of advanced nanomaterials tailored to address major societal challenges in environmental protection, healthcare, and sustainable industry.

The early stage of research (2001–2009), conducted during doctoral studies, focused on the chemical stabilization of cellulosic materials subjected to natural degradation. Through systematic investigation of degradation mechanisms, innovative stabilization treatments, and non-conventional pretreatment techniques, this period established strong expertise in surface chemistry, material durability, and interface engineering. These foundational competencies enabled the transition toward nanoscale material design and functional surface modification.

The postdoctoral stage (2010–2013) marked a significant diversification of research directions. A major focus was placed on nanomaterials for pharmaceutical safety and environmental remediation, including the development of nano-structured photocatalysts for the degradation of pharmaceutical contaminants and the synthesis of nanocomposites for radioactive effluent treatment. Detailed analyses of degradation pathways, stability under UV and visible irradiation, and advanced oxidation processes contributed to understanding the environmental behavior of active compounds and to proposing efficient decontamination strategies.

In parallel, functional nanomaterials for controlled drug delivery were developed, particularly mesoporous silica-based systems and other nano-carriers. Studies addressed loading capacity, structural and thermal stability, diffusion mechanisms, and morphology–performance correlations, providing essential insights for optimizing release profiles and preserving therapeutic efficacy.

A complementary research direction involved smart textiles engineered via nanotechnology. Functional coatings incorporating ZnO nanoparticles were designed to impart antimicrobial activity, UV protection, and enhanced thermal behavior. Surface engineering techniques—including plasma treatments and hybrid functionalization—enabled hydrophobicity, improved air permeability, and increased comfort. Composite textiles with adsorptive properties were also developed for environmental and protective applications, demonstrating the transformation of conventional fabrics into active, multifunctional materials.

Subsequent research expanded toward biocompatible nanoporous materials doped with bioactive nano-oxides (silica, silver, ZnO) for antibacterial coatings, controlled release systems, and tissue regeneration scaffolds. Antimicrobial hydrogels based on PVA/agar matrices loaded with essential oils and plasma-activated biopolymeric microcapsules deposited on natural fibers further illustrate the integration of sustainability and advanced functionality in biomedical and textile applications.

Between 2013 and 2020, research emphasized industrial applicability and technology transfer, consolidating scientific leadership through collaborative projects and publications in high-impact (Q1–Q2) journals. From 2020 onward, the portfolio integrated nanofluids and mathematical modeling, developing predictive models for non-Newtonian biological fluids and nanofluid flow, with applications in bioengineering, heat transfer optimization, and microsystems. This integration of experimental and computational approaches reflects the maturation of a holistic and interdisciplinary research strategy.

Overall, the thesis demonstrates thematic coherence, sustained scientific productivity, and significant contributions to advanced nanomaterials engineering. It establishes a solid foundation for independent research development, doctoral supervision, and the advancement of innovative solutions in environmental and biomedical fields.